Multi-Criteria Cost Effectiveness Using a Water Quality Index

Charles Griffiths
National Center for Environmental Economics

EPA NCEE Symposium on Cost Effective Analysis for Multiple Benefits
September 9, 2003

Two Major Water Quality Laws

- Safe Drinking Water Act (SDWA)
- ***Clean Water Act (CWA)***
  - eliminate the discharge of pollutants into navigable waters
  - provide water quality for the protection of fish, shellfish, and wildlife and for recreation in and on the water
  - prohibit the discharge of toxic pollutants in toxic amounts

Technology-Based Limits

- <u>Best Practicable control Technology (BPT)</u> - determined for all pollutants
- <u>Best Conventional control Technology (BCT)</u> - stricter limit for conventional pollutants (biological oxygen demand (BOD), total suspended solids (TSS), fecal coliform, pH, and oil and grease)
- <u>Best Available control Technology (BAT)</u> – stricter limit for toxic and non-conventional pollutants

Best Practical Technology (BPT)

"Factors relating to the assessment of best practical control technology … shall include **consideration of the total cost of application of technology in relation to the effluent reduction benefits to be achieved from such application**"

Section 304 (b)(1)(B)

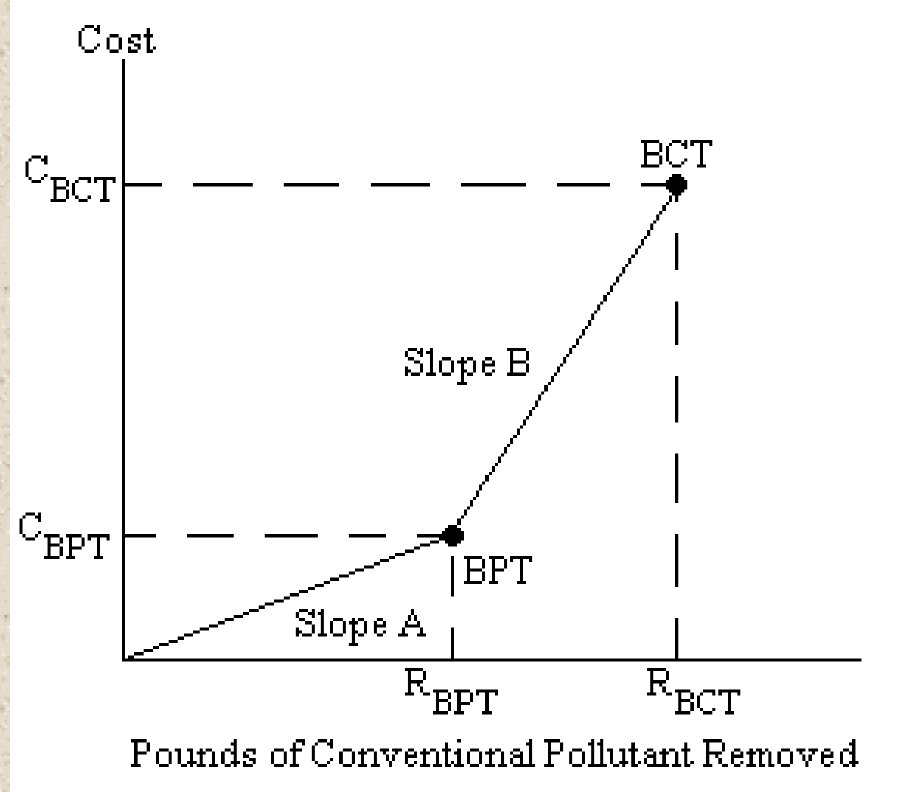
Best Conventional Technology (BCT)

"Factors relating to the assessment of best conventional pollutant control technology … shall include **<u>consideration of the reasonableness of the relationship between the costs of attaining a reduction in effluents and the effluent reduction benefits derived</u>**, and the **<u>comparison of the cost and level of reduction of such pollutants from the discharge from publicly owned treatment works to the cost and level of reduction of such pollutants from a class or category of industrial sources</u>**" Section 304 (b)(4)(B)

NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

BCT Cost Reasonableness Test

- BPT - The average of the best
- BCT
  - Incremental cost per pound removed, slope B, must be less than $0.25 per pound in 1976 dollars
  - Incremental cost effectivness is no more than 29 percent of BPT. That is, the ratio of slope B to slope A is less than 1.29



Toxicity Weighted Pounds Removed

$$3(R_T)*(TWF)$$

R_T = Pounds Removed of Toxic Pollutant

TWF = Toxic-weighting factor

$$TWF = (5.6/C) + (5.6/H)$$

C = Aquatcic life chronic criterion value, µg/L

H = Human health criterion value, based on ingesting 6.5 grams of fish per day, µg/L

5.6 = 1980 chronic freshwater criterion for copper, µg/L

Cost Effectiveness for Multiple Pollutants

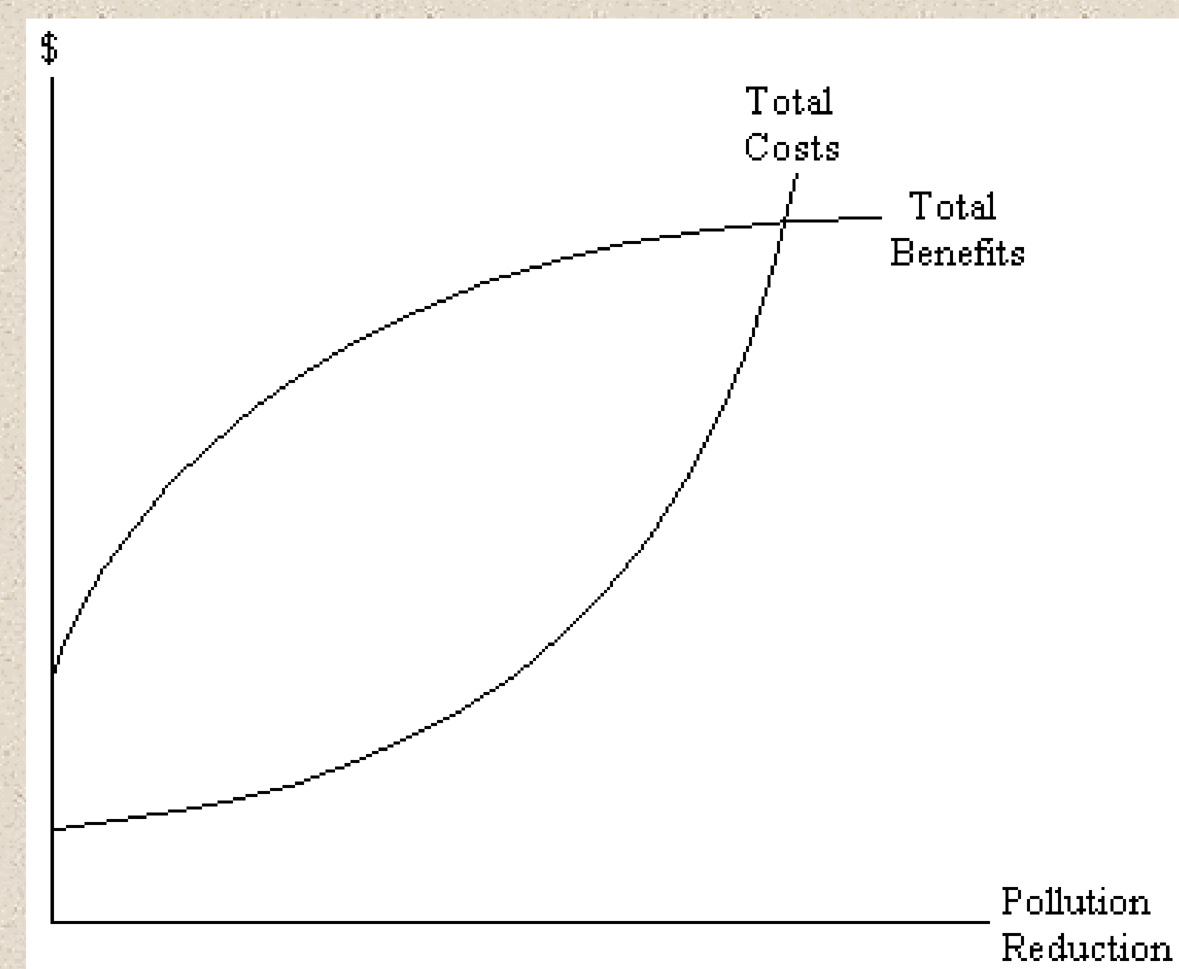
- Add total pounds removed
- Evaluate pollutant with worst cost-effectiveness ratio
- Form a weighting scheme (e.g., toxicity weighed pounds)
- ***Water Quality Index***

Cost Effectiveness Analysis

- Identifies the least costly way of achieving a particular objective (e.g., the minimum cost per ton of reducing an effluent)
- Generally done when the objective can only be quantified along some non-monetary dimension
- Helps select between options, but is silent on whether or not the project should be undertaken
- The benefits of the project must be related to the non-monetary dimension upon which it is evaluated (e.g., benefits society receives from the project are correlated with the reduction in pounds of the effluent)
- Cost effectiveness is simply the inverse of the benefit to cost ratio

Cost Effectiveness vs. Net Benefits

- Benefits
  - B(x) > 0
  - BN(x) > 0
  - BO(x) < 0
- Costs
  - C(x) > 0
  - CN(x) > 0
  - CO(x) > 0



Maximum Benefit/Cost Ratio vs. Maximum Net Benefits

- Maximum Benefit/Cost Ratio:

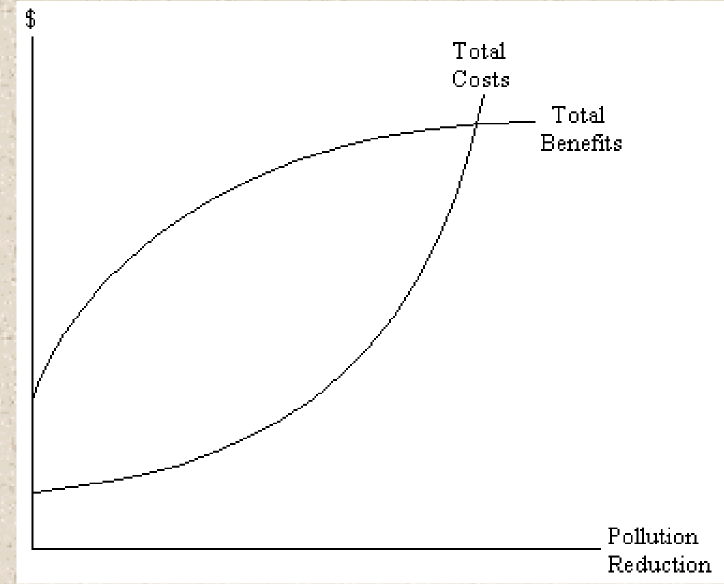
$$\frac{\partial\left(\frac{B(x)}{C(x)}\right)}{\partial x} = \frac{B'(\tilde{x})C(\tilde{x}) - B(\tilde{x})C'(\tilde{x})}{\left(C(\tilde{x})\right)^2} = 0$$

$$\Rightarrow B'(\tilde{x})C(\tilde{x}) = B(\tilde{x})C'(\tilde{x}) \Rightarrow \frac{B'(\tilde{x})}{B(\tilde{x})} = \frac{C'(\tilde{x})}{C(\tilde{x})}$$

- Maximum Benefit-Cost Value:

$$\frac{\partial[B(x) - C(x)]}{\partial x} = B'(x^*) - C'(x^*) = 0$$

$$\Rightarrow B'(x^*) = C'(x^*)$$



NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

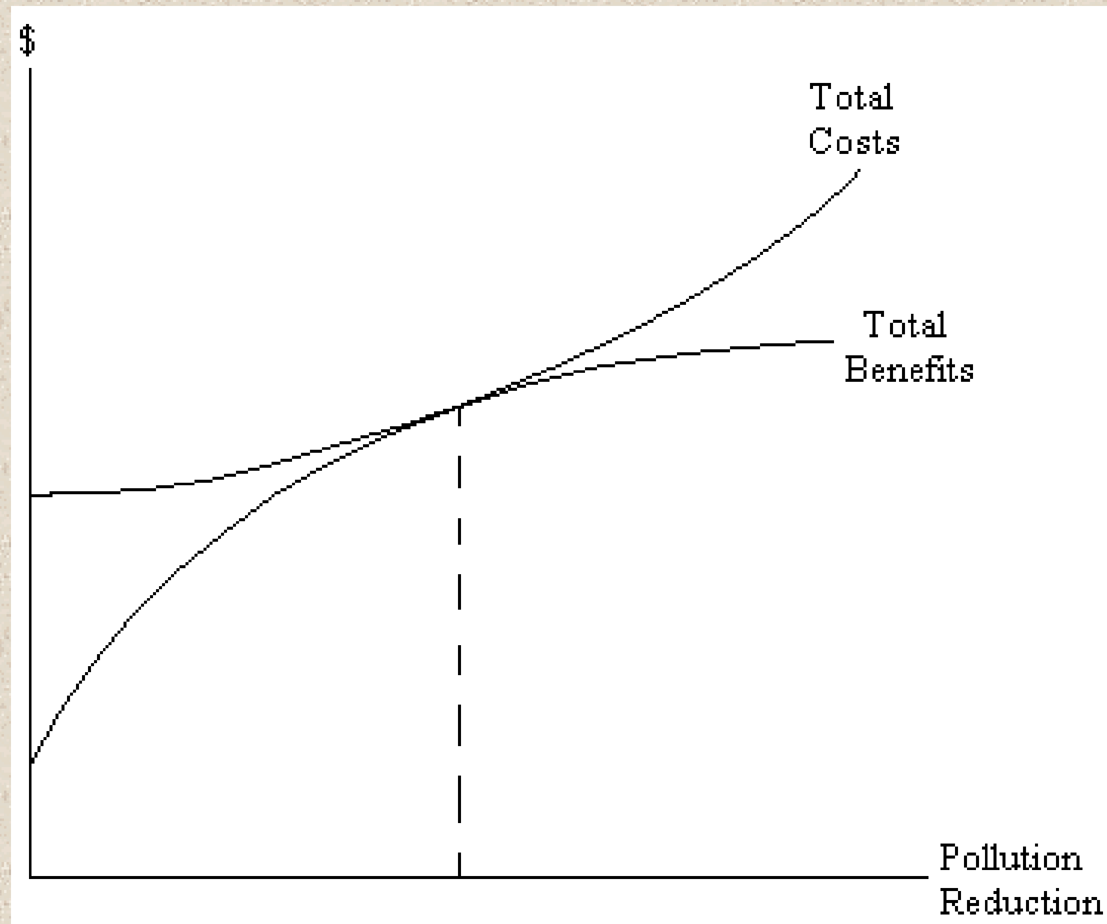
Equivalency of Maximum Benefit/Cost Ratio and Net Benefits

- Benefit/Cost Maximum:

$$\frac{B'(\tilde{x})}{B(\tilde{x})} = \frac{C'(\tilde{x})}{C(\tilde{x})}$$

- Net Benefit Maximum:

$$B'(x^*) = C'(x^*)$$



Proof: Benefit/Cost Maximum < Net Benefit Maximum

- Net benefits are maximized where BN(x*) = CN(x*)N
- Benefit/cost ratio is maximized when BN(x)C(x) - B(x)CN(x) = 0
- At x*, when net benefits are maximized and BN(x*) = CN(x*)

BN(x*)C(x*) - B(x*)CN(x*) = BN(x*)C(x*) - B(x*)BN(x*) = BN(x*)[C(x*) - B(x*)]

- Since BN(x*)>0 and we are assuming that benefits are greater than costs, then BN(x*)[C(x*) - B(x*)] < 0
- Since the first derivative is declining, we have gone passed the value that maximizes the benefit/cost ratio

Implications: Benefit/Cost Max < Net Benefit Max

- The pollution reduction that maximizes the benefit/cost ratio is unambiguously less than the pollution reduction that maximizes net benefits
- If effectiveness is directly related to benefits, then we can increase pollution reduction to the minimum cost effectiveness point and be assured that we have not increased pollution reduction beyond the point of maximum net benefits

Multicriteria Water Quality Index

$$I = f(s(x)) \; 0 \; (0,1)$$

where I = aggregate water quality index

f(·) = aggregation function

s(x) 0 (0,1) = subindex for an individual pollutant

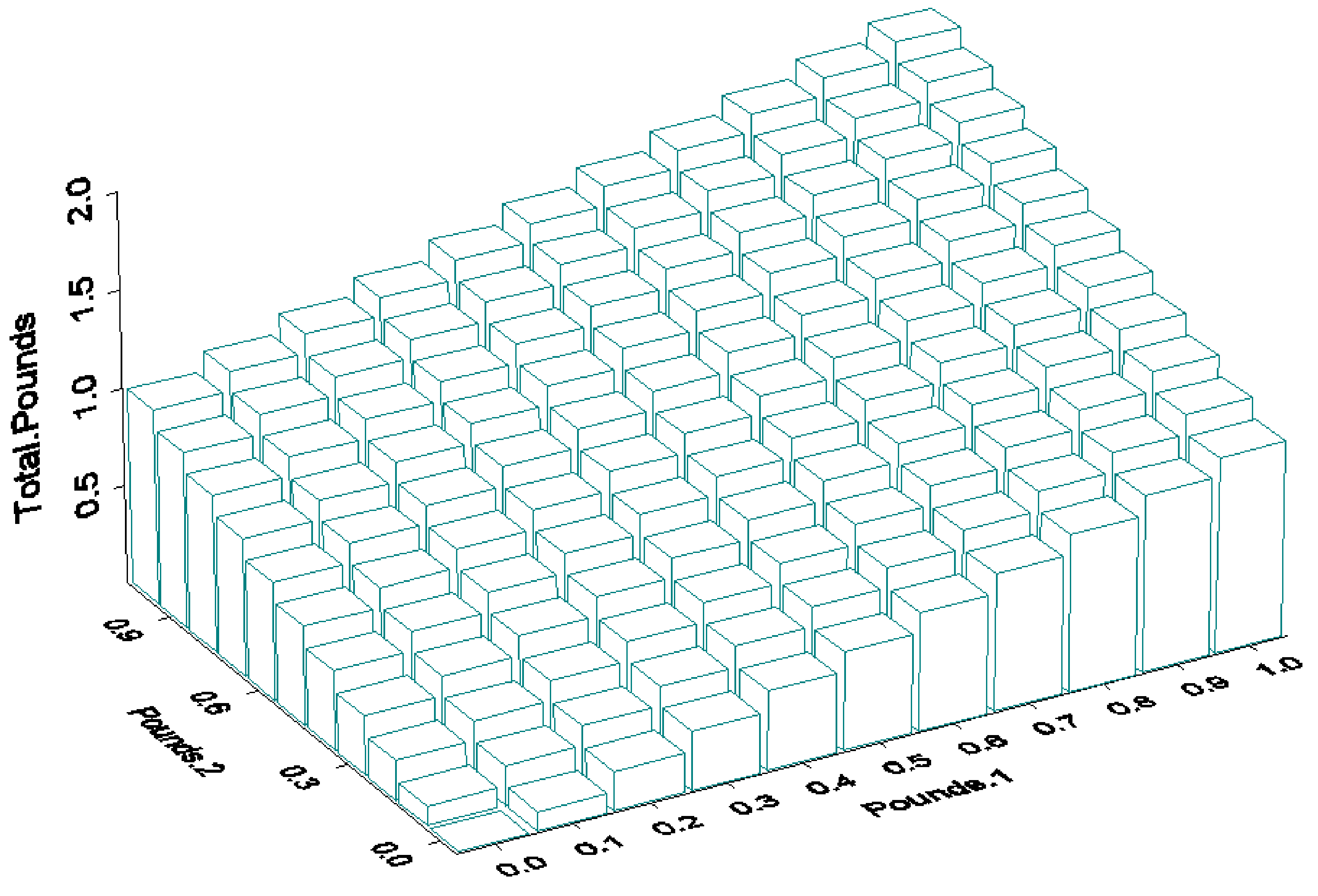
x = individual pollutant or physcial effect

National Sanitation Foundation Subindicies

- Survey of 142 U.S. experts
- Asked to rate water pollutant variables for inclusion in a water quality index
- Follow up questionnaire to designate the fifteen most important pollutants
- Third questionnaire to assigned values for the subindices for the nine most important variables by drawing a curve
- An “average curve” for each panelist was then formed.

Parameter	**Weight**
D.O.	0.17
Fecal Coliform	0.16
pH	0.11
5-day BOD	0.11
Nitrates	0.10
Phosphates	0.10
Temperature	0.10
Turbidity	0.08
Total Solids	0.07

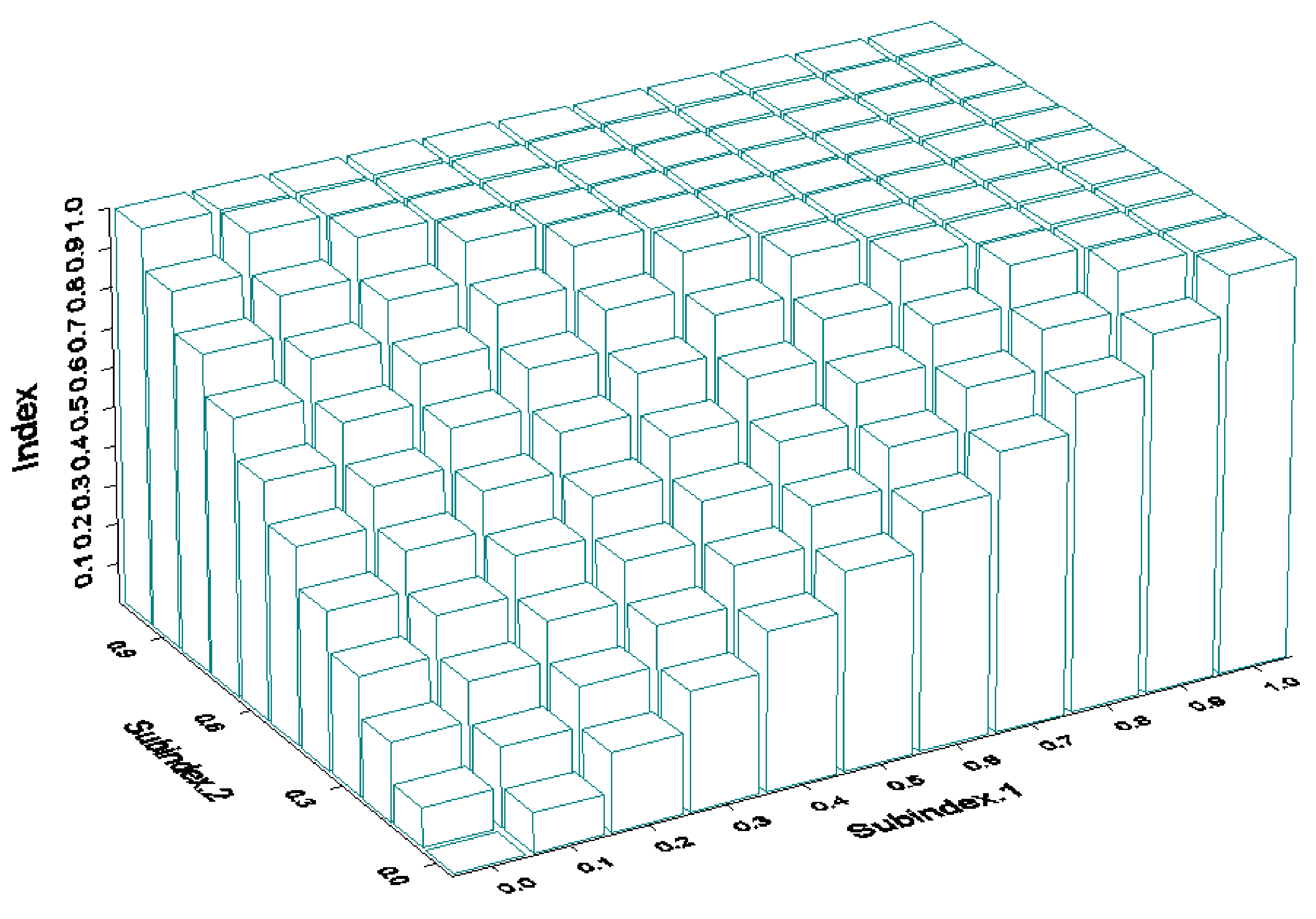
Aggregate Pounds



NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

Linear Sum

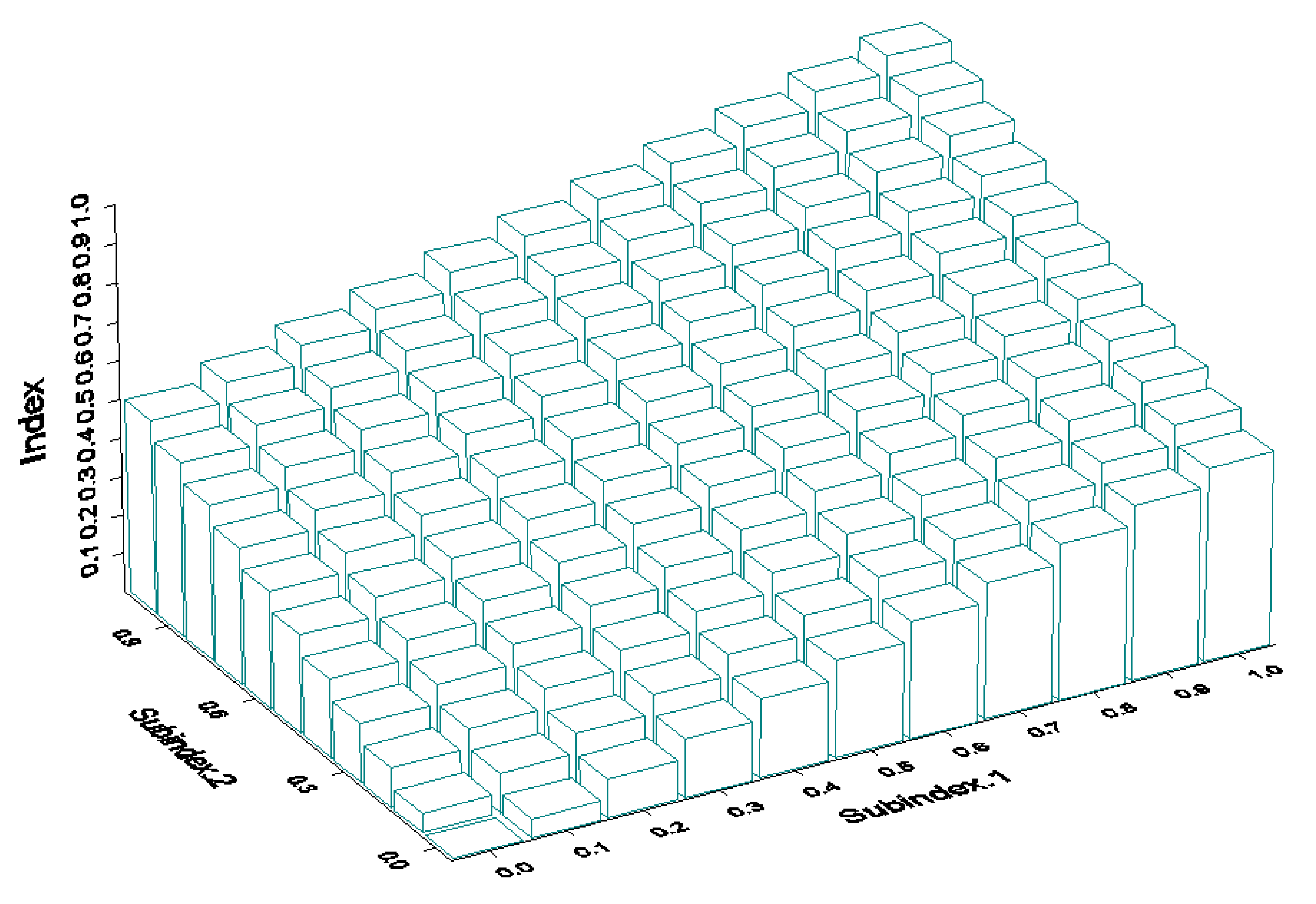
$$I = \sum_{i=1}^{n} s_i$$



NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

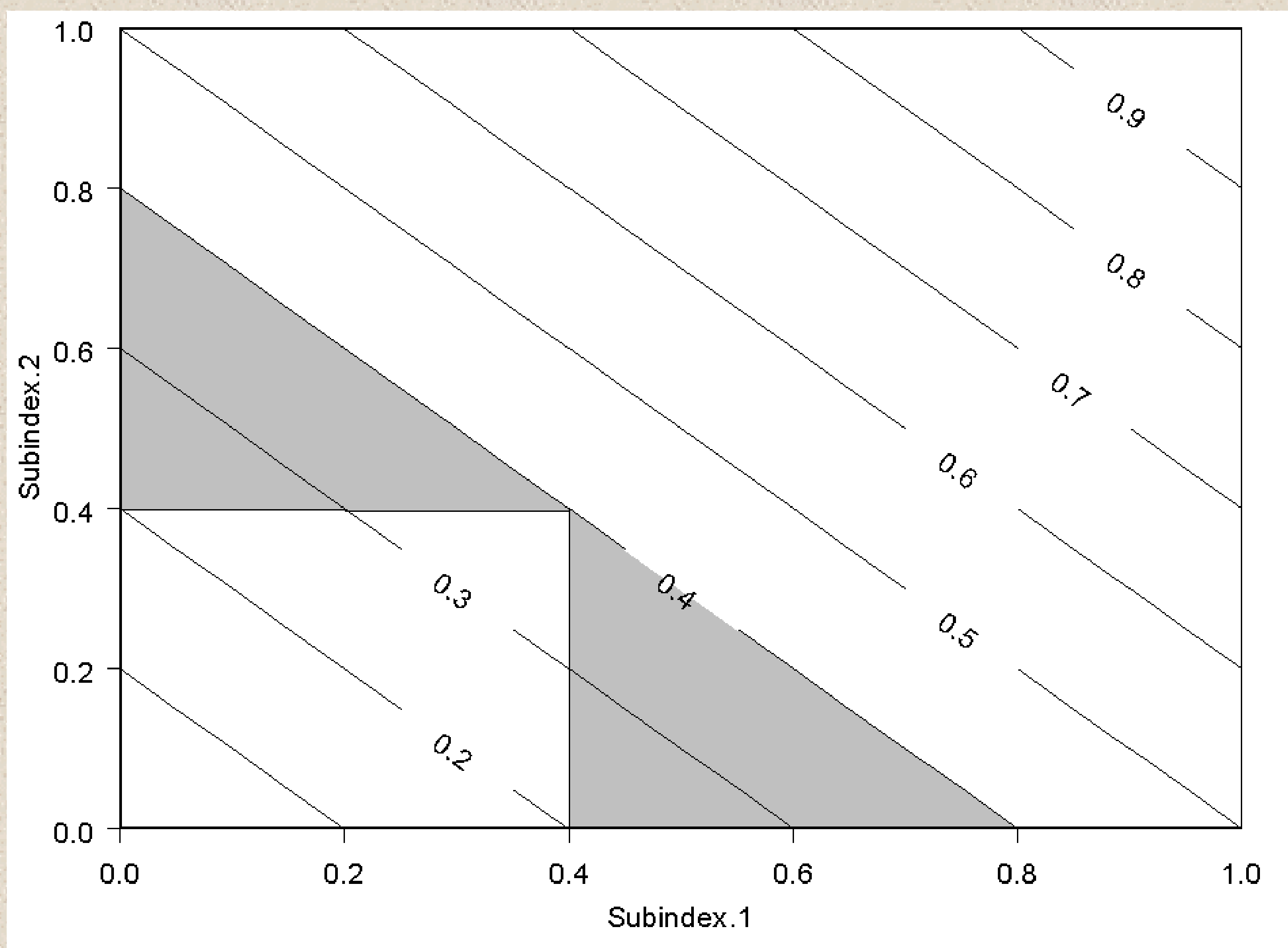
Weighted Sum

$$I = \sum_{i=1}^{n} w_i s_i$$



NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

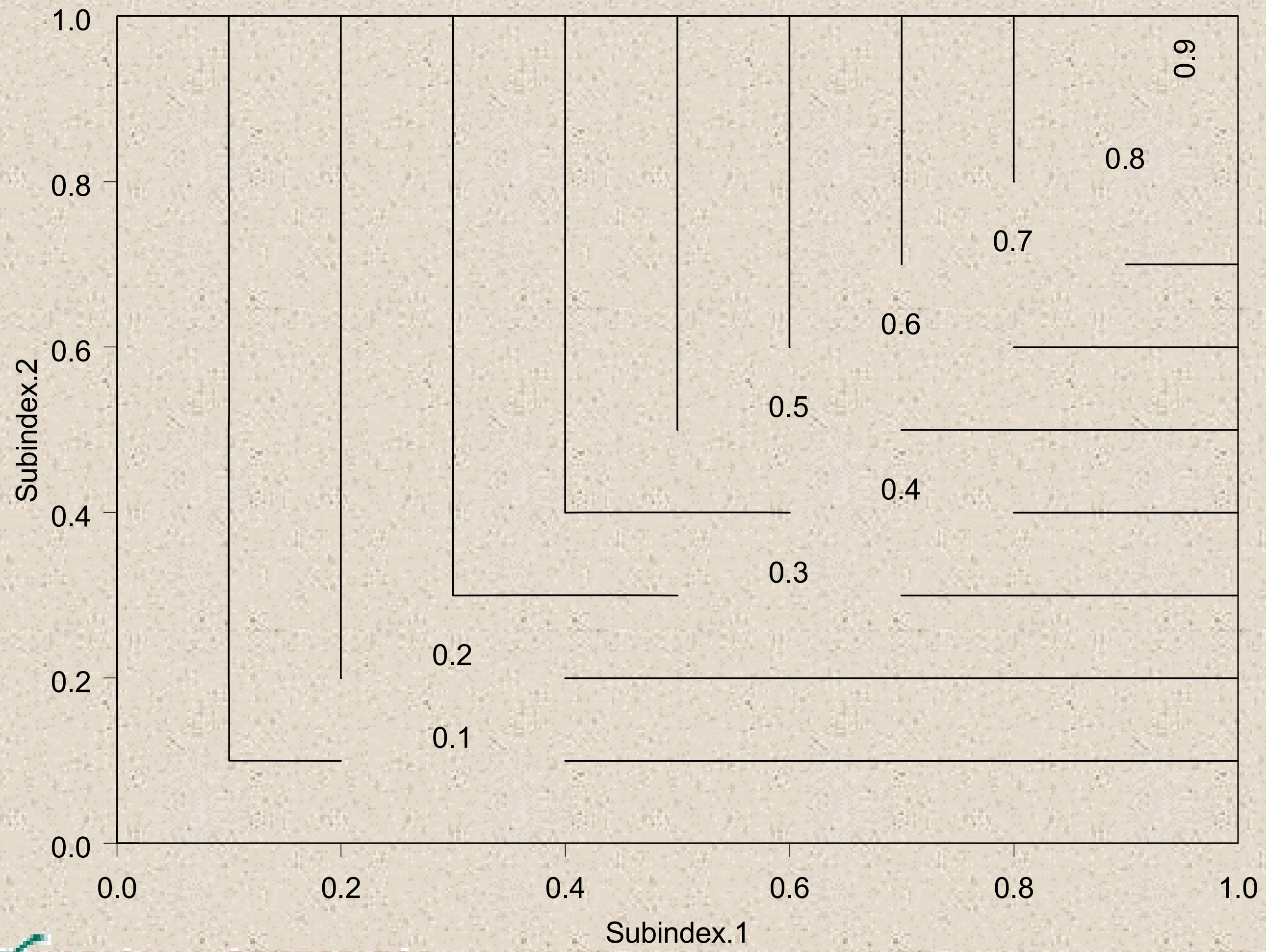
Eclipsing



NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

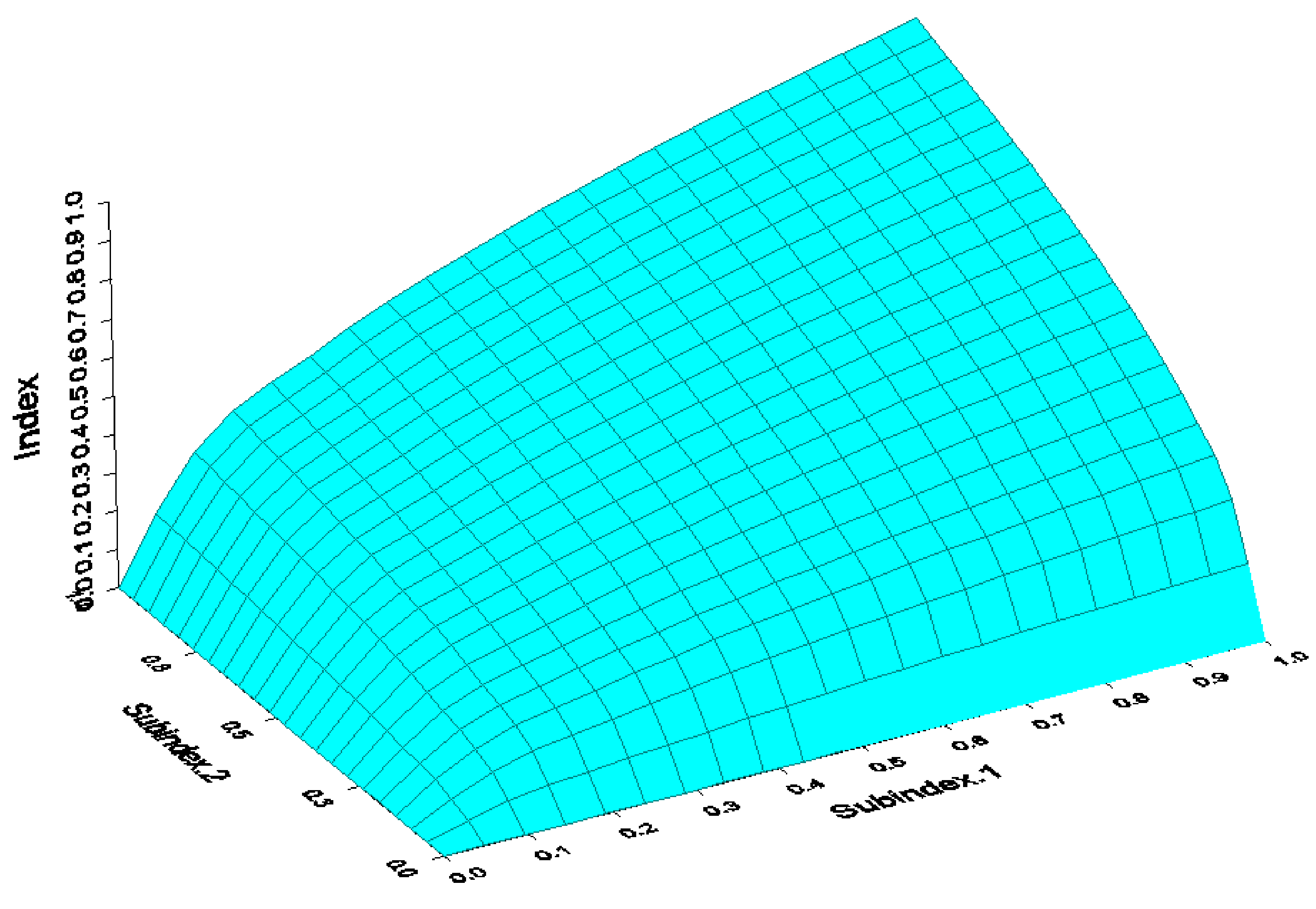
Worst Cost Effectiveness

$$I = \min\left\{\vec{s}_i\right\}$$



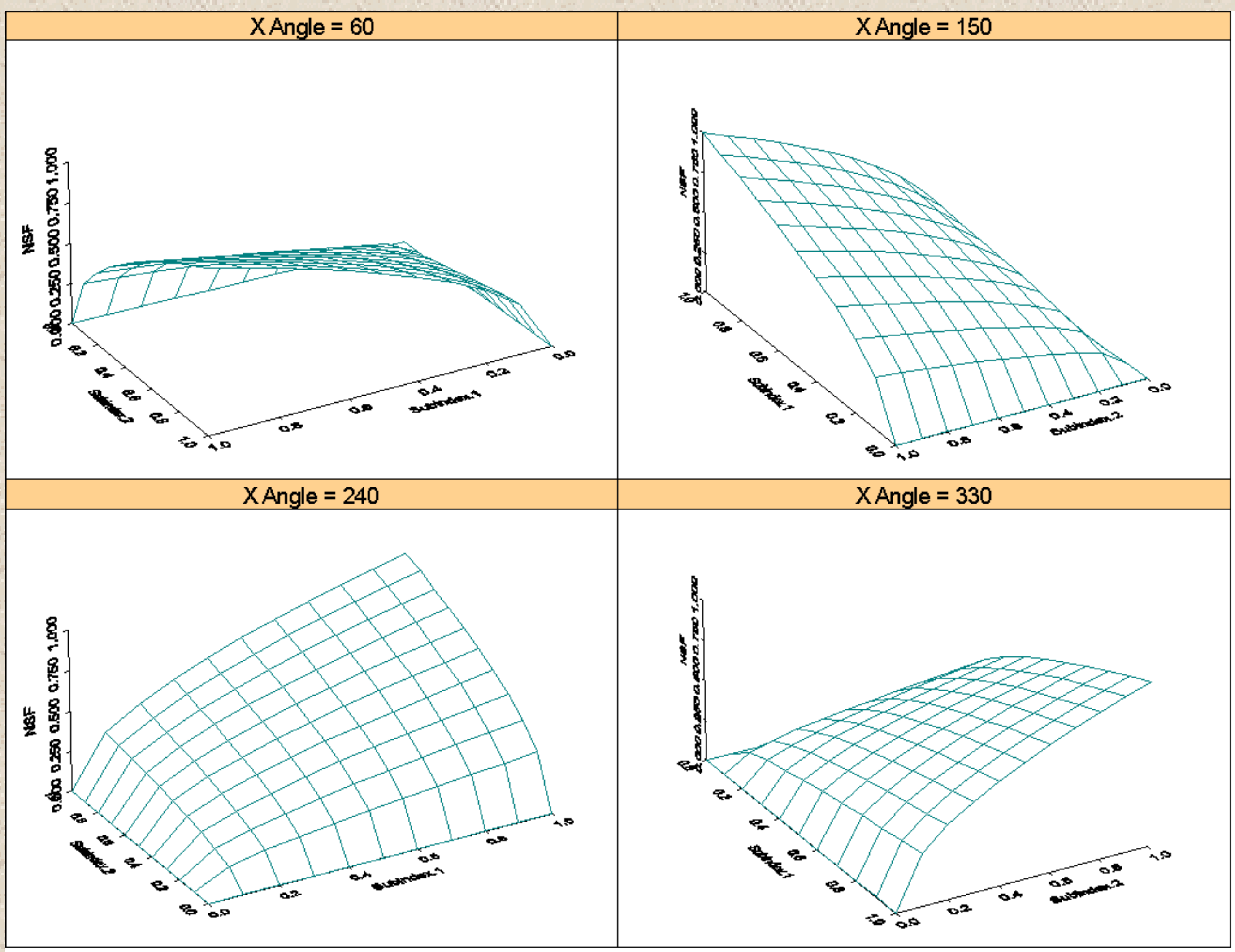
NSF Index

$$I = \prod_{i=1}^{n} s_i^{w_i}, \quad \sum_{i=1}^{n} w_i = 1$$

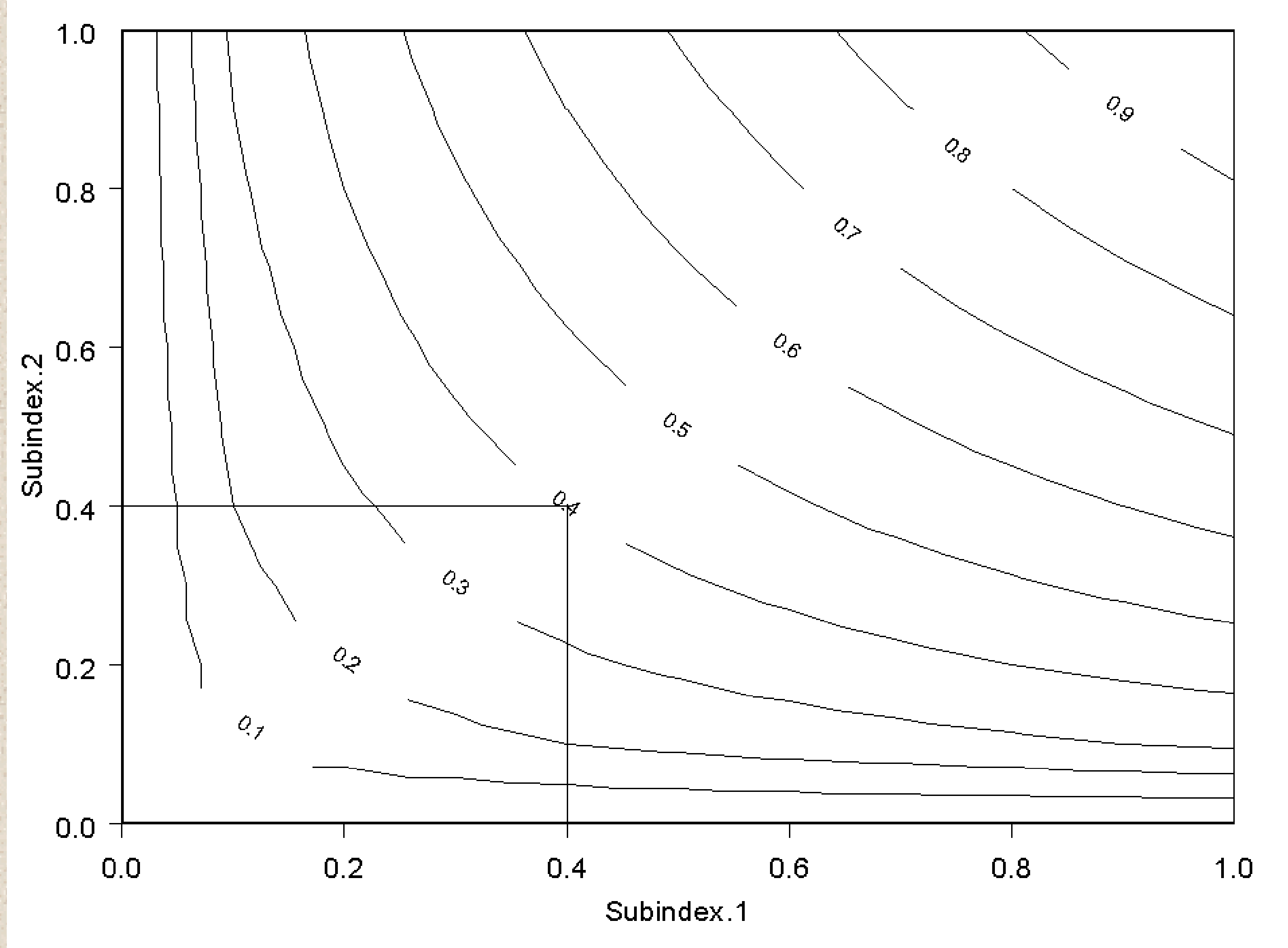


NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

NSF Index Curvature



NSF Index Plot



Water Quality Regulation using a Water Quality Index

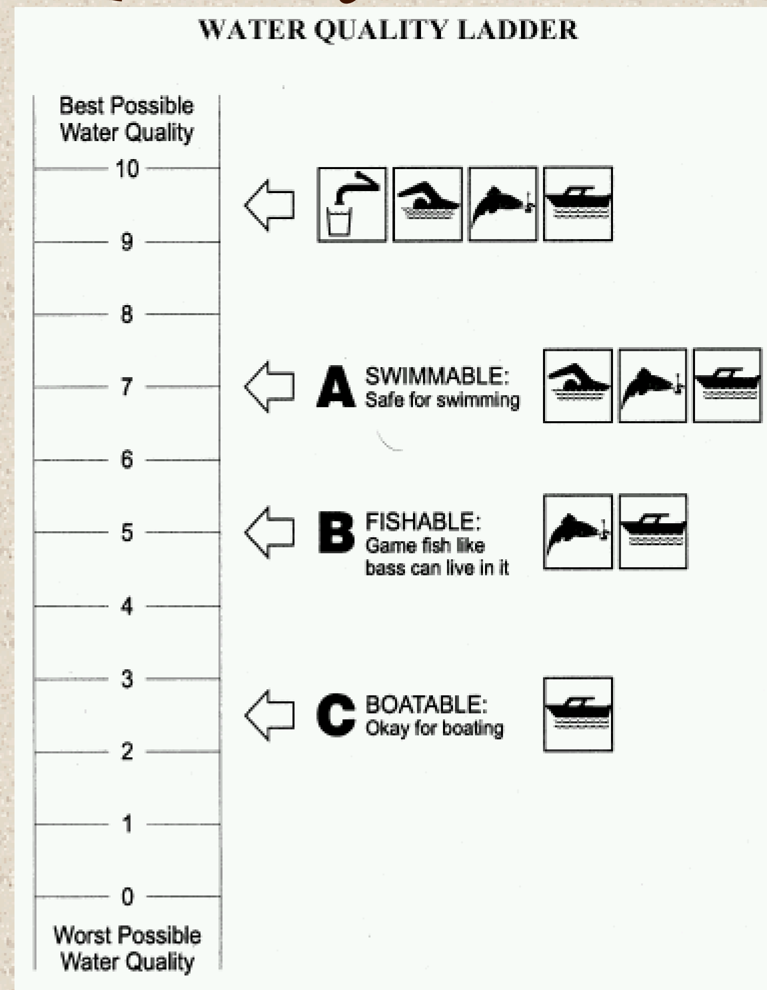
- Completed
  - Storm Water Phase II, final ELG
  - Meat and Poultry Products, proposed ELG
  - Concentrated Animal Feeding Operations, final ELG
- Under Consideration
  - Meat and Poultry Products, final ELG
  - Construction and Development, final ELG

CAFO ELG Loadings

ESTIMATED ANNUAL AFO/CAFO NUTRIENT/POLLUTANT LOADINGS TO RF3 LITE NETWORK UNDER BASELINE CONDITIONS AND REVISED STANDARDS						
Regulatory Standard	**Nitrogen (lbs/yr)**	**Phosphorus (lbs/yr)**	**Sediments (lbs/yr)**	**BOD (lbs/yr)**	**Fecal Coliforms (MPN/yr)**	**Fecal Streptococci (MPN/yr)**
Baseline	165,678,014	243,476,460	47,542,359,419	60,834,353	6.46E+21	1.11E+23
Phosphorus-Based	149,409,170	209,061,598	46,608,917,113	46,095,058	5.676E+21	8.956E+22
Nitrogen-Based	159,212,191	226,095,217	46,923,865,247	55,480,930	6.37E+21	1.07E+23

NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

Mitchell and Carson Water Quality Index



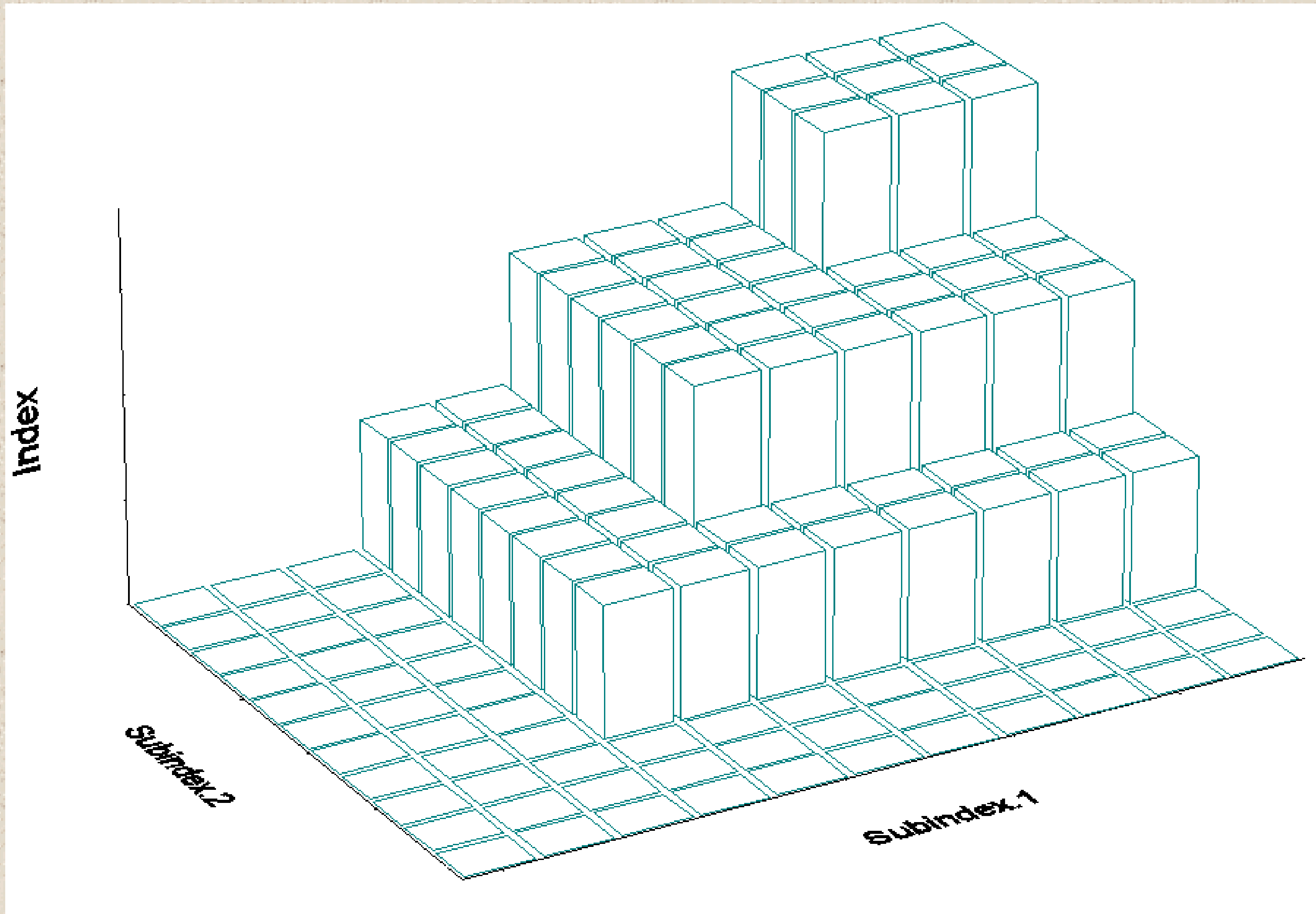
Mitchell and Carson Willingness to Pay Values

INDIVIDUAL HOUSEHOLD WILLINGNESS TO PAY FOR WATER QUALITY IMPROVEMENTS (1983 $)		
Water Quality Improvement	**Total WTP**	**Incremental WTP**
Swimmable: WTP to raise all sub-swimmable water quality to swimmable	$241	$78
Fishable: WTP to raise all sub-fishable water quality to fishable	$163	$70
Boatable: WTP to maintain boatable water quality	$93	$93

Vaughn Water Quality Ladder

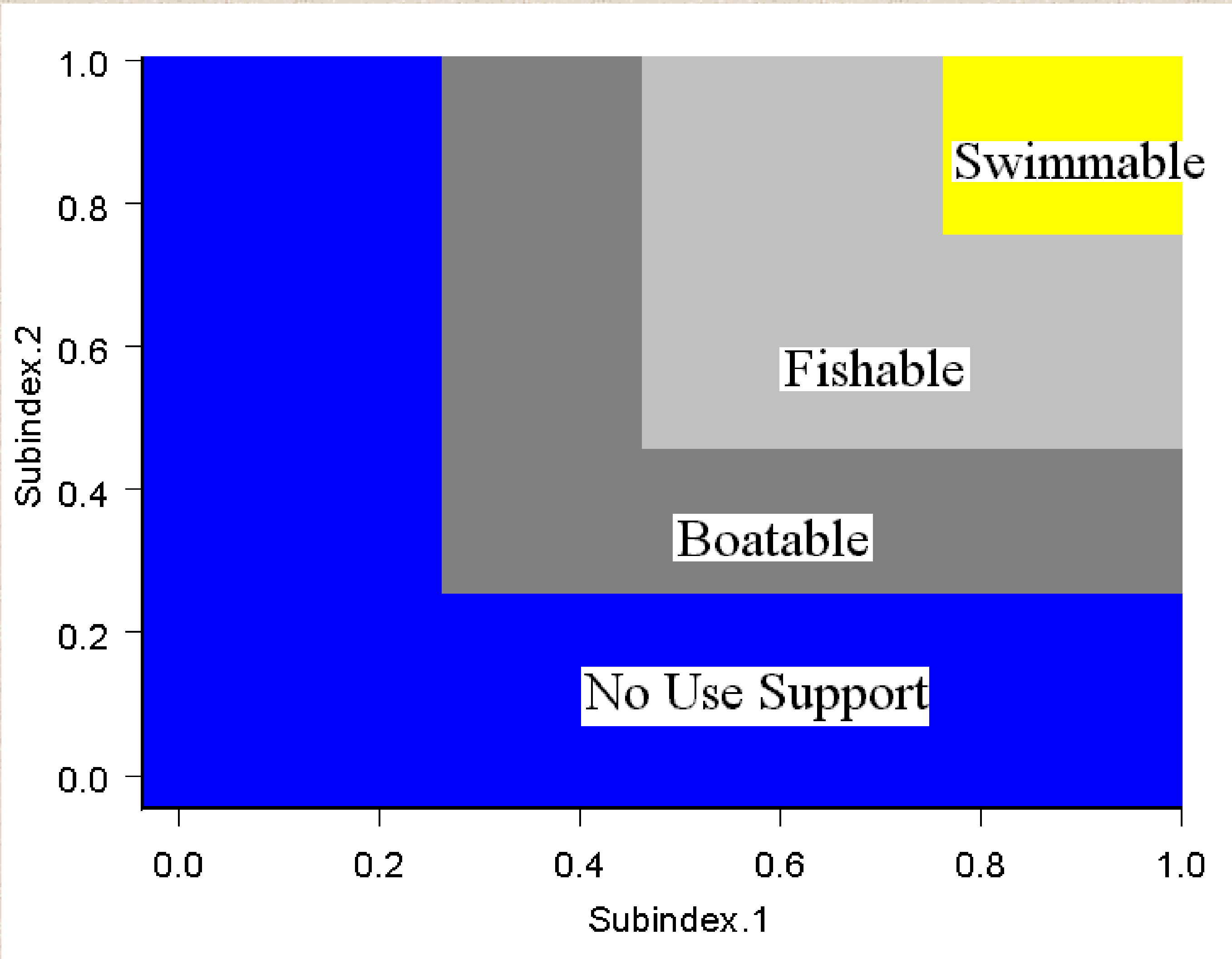
Beneficial Use	Fecal Coliforms (MPN/100 mL)	Dissolved Oxygen (mg/L) / (% sat.)	5-day BOD (mg/L)	Total Suspended Solids (mg/L)
Drinking	0	7.0 / 90	0	5
Swimming	200	6.5 / 83	1.5	10
Game Fishing	1000	5.0 / 64	3.0	50
Rough Fishing	1000	4.0 / 51	3.0	50
Boating	2000	3.5 / 45	4.0	100

Water Quality Ladder



NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

Water Quality Ladder Plot



NCEE NATIONAL CENTER FOR ENVIRONMENTAL ECONOMICS

Summary

- Cost effectiveness is currently used for BPT, BCT, and BAT determination.
- Cost effectiveness could be applied to a multicriteria water quality index.
- Cost effectiveness (and benefit/cost) optimization is not equivalent to net benefit optimization.
- The NSF index is one possible way to measure a water quality index.
- Water quality indices have been used in net benefits calculations for a number of rules, but have not been used for cost effectiveness analysis.